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Exploring stability and change in transport systems: combining Delphi and system dynamics approaches

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Abstract Transport is a vast and complex socio-technical system, and despite a clear need to reduce dependence on fossil fuels due to undesirable environmental impacts, it is largely locked into business-as-usual. Systems approaches are a useful way to help make sense of multiple competing influences which may be simultaneously driving change and supporting the status quo. This paper applies qualitative system dynamics modelling to help interpret the results of a Delphi study into global transport transitions, involving 22 international experts in various aspects of transport. The main contribution of the paper is its exploration of the use of system dynamics (SD) modelling to interpret the Delphi findings. SD modelling was used to reveal and elucidate the causal arguments put forward by the expert panel about the factors driving business-as-usual, the factors creating barriers to more sustainable transport systems, and the drivers of change. The SD model is used to explore and expose the key causal patterns at play, and how these interact to both support and hinder change. The resulting model shows the complex, interdependent dynamics involved in supporting the status quo. Even at the relatively high level of analysis reported here, the model is useful in revealing interdependencies between parts of the system, where change in one part may well have knock-on effects elsewhere in the system. In particular the model reveals the strong reinforcing loops that act to minimise the impact of change drivers and thus retain the dominance of automobility. The result is a system that is highly dependent on the continued existence of key reinforcements such as policies that subsidise fossil fuels. From a methodological perspective, the outcomes of the Delphi study provided a rich source of qualitative material which was highly suitable for developing a system dynamics model.

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Introduction

The global dominance of transport systems that rely on fossil fuels and support automobile dependence, together with the continuing growth in both passenger transport and freight activity, are at odds with the urgent need to reduce transport-related greenhouse gas emissions (Chapman 2007, Sims and Schaeffer 2014). Transitioning away from the status quo, however, is far from straightforward, as it involves changes to a vast, complex system, with many interdependencies and feedback loops. The socio-technical (Geels 2002, 2004, 2005) nature of the system, involving interplays between technology, infrastructure, policy, regulation, user practices, and social norms means that identifying appropriate interventions for change requires the use of models and tools that are able to handle the interactions of diverse societal and technical factors. Systems dynamics (SD) modelling is one such tool.

This paper applies SD modelling to help interpret the results of a Delphi study involving an international panel of experts which examined stasis and change in transport systems globally. SD modelling was used to help in the analysis of the study results, to elucidate the causal arguments put forward by the panel about the factors driving business-as-usual, the factors creating barriers to more sustainable transport systems, and the drivers of change. The SD approach thus assisted in exploring the key causal patterns at play, and how these patterns interact to both support and hinder change. The paper presents a qualitative causal map based on the Delphi findings.

As the 22 Delphi panel members were from many parts of the globe, we focused our analysis on shared observations about transport systems in the developed and developing nations and regions with which panel members were familiar. While we recognise that each country is unique, the transport systems of industrialised countries are in many ways globalised systems, with similar technologies, fuels, and similar sets of drivers, differing by degree rather than fundamentally, and largely consistent with what Urry refers to as a ‘system of automobility’ (2004).

Applications of system dynamics modelling to transport

Transport is a complex socio-technical system (Watson 2012), reflecting the “dependencies and co-evolution of infrastructure and institution, technology and society” (Whitmarsh 2012, p. 484). A dynamic model that captures the interrelationships between parts of the system is a valuable tool for exploring transport systems (Abbas and Bell 1994). It is therefore unsurprising that system dynamics, designed as it is to make order from complexity (Forrester 1961), has been widely used in wide ranging transport research (Shepherd 2014) including aviation (Sgouridis et al. 2011), land transport (Struben and Sterman 2008), and multimodal travel (Leve et al. 2014).

Abbas and Bell (1994) argued that SD modelling is particularly useful for “1. Understanding and explaining the dynamic behaviour of a system in terms of its structure (causal relations and feedback loops) and policies, as well as improving the conceptual models that explain the system; 2. Designing, formulating and testing different scenarios and policies by posing and answering "what if" questions; 3. Providing useful information, both to policy- and decision-makers, thus giving support to the decision-making process in the field of strategic planning; and 4. Improving the management and control of complex systems" (p. 382). And thus, this approach is particularly well-suited to the study of the transportation system which is multi-dimentional, complex, and large-scale. In relation to transport transitions, SD modelling has been used to examine transport and energy security (Martinez-Moyano et al. 2012) and the impact of new fuels (Schade 2012). Struben and Sterman (2008) employed SD modelling to examine the diffusion low-carbon vehicles, which allowed the pinpointing of critical thresholds for adoption of hybrid vehicles and hydrogen fuel cells.

SD modelling has also been used to support policy development and evaluation in transport, relating to topics including new technology uptake, and traffic law violations (Mehmood 2010). Ford (1995) modelled the potential for feebates to encourage the sale of cleaner vehicles, and Leaver and Gillingham (2010) assessed the economic impact of the uptake of hydrogen fuel cells, hydrogen internal combustion and battery electric technologies. In exploring urban car dependency, Bachels et al. (1999) used SD modelling to identify the positive feedback mechanisms related to policy on transport and land use planning. Another policy application arises from Fiorello et al. (2010) who simulated energy scarcity, high oil prices, technological investments and specific transport policies across the European Union and presented a range of alternative scenarios considering linkages between transport demand, the economy, the vehicle fleet and the natural environment.

SD modelling has thus been usefully applied to a range of transport topics, including examining transport systems at a high level to understand the implications of different future contexts. The sources of data for these models vary considerably, from direct empirical research and reviews of reports and literature, to consultation with stakeholders and subject matter experts (Luna-Reyes and Andersen 2003).

Central to the modelling methodology is the view that empirical data alone is insufficient to model a system; it is crucial to also draw from qualitative understandings of the dynamics of complex systems. Accordingly, interviews and workshops with experts are commonly used in model building as they have already developed 'mental models' of cause and effect from a well-informed basis. Eskinasi et al. (2009), for example, involved stakeholders and policymakers to develop an SD model in an urban transport context and found that the process yielded counterintuitive insights which may have been otherwise missed, and helped stakeholders to work through contentious issues. These collaborative approaches to model building, often referred to as Group Model Building (Vennix 1996, Luna-Reyes and Andersen 2003, Richardson 1991), all share the same underlying viewpoint that involving client groups and subject matter experts in the model building process, especially in matters of policy and strategy (Luna-Reyes et al. 2006) is important but also challenging. One such process that can been used to capture qualitative data is the Delphi method.

Delphi studies are recognised as an appropriate and valuable source of qualitative data for SD modelling (Luna-Reyes and Andersen 2003) and have been used in forecasting future transport scenarios (e.g. Heiko and Darkow 2010). We have been unable to find any transport studies that have used the combination of Delphi study and SD modelling, although this combination has been used health systems (e.g. Vennix and Gubbels 1992, Vennix et al. 1992) and supply chain management (Angerhofer and Angelides 2000).

In this paper, we explore the possibilities of using the combination of SD modelling and the Delphi technique to explore the drivers of stasis and change in transport systems. In the next sections we describe the specific SD approach used, and Delphi methodology. We then develop a qualitative SD model out of the cause-and-effect statements expressed by the Delphi panel. By combining and comparing the perspectives and 'mental models' of multiple experts, using the structure of SD modelling, we aim to explore the use of SD modelling to interpret Delphi findings, as well as a robust interpretation of the principal dynamics of the dominant transport system.

Methods

The system dynamics approach

While the use of modelling to examine transport system behaviour is not new, SD differs from other formal modelling techniques often used in transport research (Hensher and Button 2000) in several ways. First, it highlights feedback processes - circular causal relationships, in which variables influence and, in turn, respond to each other (Richardson 1991). The notion of linear causality is replaced by the recognition of reciprocal, causal relationships amongst multiple variables linked together in a structure of mutual causality (Dent 2003). The resulting web of relationships is the important unit of analysis in SD, a higher conceptual unit than the variables themselves.

Second, SD modelling focuses on cause and effect, being explicit about the causal relationships between variables and highlighting the consequences of these interactions. The models are also able to represent the delays that may exist between actions and the effects that arise from them, thus bringing them closer to the realities of systemic change (Forrester 1992).

Different forms of SD modelling are useful for different purposes. If SD models are quantified and then simulated, they are able to track the future trajectory of interdependent variables, incorporating the dynamics of feedback and time delays at work within the system. However, an earlier stage of any model-building is to qualitatively represent the key influences and feedback loops in the system under study, a technique known as causal mapping (Wolstenholme 1990). Expert knowledge is especially helpful in helping establish the multiple causal connections existing in a system, particularly when building off collective expert understandings. As the founder of the discipline puts it:

> "…vast amounts of information exist in the minds of those participating in the particular social system. To ignore this information is to cut off our greatest source from which we may learn…." (Forrester 1968, p. 612).

In this paper we use the SD technique of causal mapping to investigate and map the perspectives of the international transport sector experts involved in a Delphi study. The precise steps of the mapping process are detailed in the Sect. Developing the SD model.

The Delphi technique

The Delphi technique is an iterative, multi stage process of inquiry involving a panel of subject experts (Hasson et al. 2000). It is commonly employed in research on complex topics, in order to bring together diverse perspectives on a problem, and to explore levels of agreement or disagreement. Delphi studies are frequently used in future forecasting (Weaver 1971) and have been used in a diverse range of settings, from healthcare to bioenergy (Gibson 1998, Rikkonen and Tapio 2009). The method "operates on the principle that several heads are better than one in making subjective conjectures about the future, and that experts … will make conjectures based upon rational judgment and shared information…" (Weaver 1971, p. 268). It lends itself to interdisciplinary issues which incorporate physical, social, policy and economic perspectives, and is therefore particular suited to an examination of the dominant global transport system.

A panel of twenty-two global transport experts was recruited from industry, policy, academia and non-governmental organisations. Their expertise spanned vehicle and battery technologies, freight, fuels, behaviour and policy. The panel was knowledgeable about transport systems in North America, the UK and Europe, the Middle East, Asia, and Australasia. Through these participants we were able to access wide-ranging perspectives on the drivers of and barriers to change in transport systems over much of the industrialised world.

The Delphi process involved four rounds of inquiry, each building on the responses from the previous round, and this paper reports on the findings from the first two rounds. The first involved a series of qualitative, semi-structured interviews with a subset of the participants (n = 6) to scope the 'landscape' of transport and the perceived causes of stasis and change (Stephenson et al. 2014). This was followed by an online qualitative survey which invited free-text responses on the influences that support the continuation of business-as-usual (BAU); the ways in which BAU might be seen as a threat to society, economy or environment; and influences that may in future drive a shift away from BAU, with a particular focus on trends, innovations and possible discontinuities. BAU was defined in the survey as 'continuation of transport systems and practices that rely on finite resources and support automobile dependence'.

In the third round, the panel members were provided with a summary of findings from the previous round, and asked to quantify the likelihood of the most commonly-mentioned change drivers occurring, and the transformative impact those events could have on the transport system. The fourth round returned to interviews with panel members on some specific questions. The findings from these latter two rounds will be reported on separately.

Following each round of the Delphi research, thematic coding and analysis was independently undertaken by two members of the research team. The results showed a high level of agreement between the analysts, and the data used below are sourced from this common pool of data. The Delphi participants were not aware that SD modelling would be used to analyse the data.

Developing the SD model

All models are necessarily partial representations, and what is included is largely determined by decisions made in the initial model conceptualisation. In most instances the factors to be represented are determined by the modellers themselves. For example Bachels et al. (1999), who also used a qualitative SD model to study the relationship between transport choices and land use policies, chose to focus on urban form, transport provision, traffic management and traffic demand management. In our study, the scope of the model and its core constructs were not predetermined by the modellers because our interest was in exploring the ideas proposed by the panel members to see what, collectively, they had to say about the dynamics of stasis and change in transport systems. The scope of the model was therefore determined by the ideas expressed by the members of the Delphi panel.

More specifically, the purpose of our model was to develop a causal map that reflected the theories of change put forward by the Delphi panel. In this context we understand theory as "consisting of constructs linked together by propositions that have an underlying, coherent logic and related assumptions" (Davis et al. 2007, p. 481). The themes arising out of the first two rounds of the Delphi study provided the constructs for a potential theory of change in transport systems. While no individual panel member was asked for, or provided, a comprehensive theory, the SD model used the panel's thematicised statements about cause and effect, to develop a more comprehensive and integrated understanding.

Table 1 Examples of coding

Coding category	Construct	Proposition
Theme	Constructs that illustrate the theme	Descriptions of how one construct influences another and/or may change over time
Availability and price of oil	The other driver I suppose is peak-oil, so-called, and where is the fuel going to come from and is that going to change the mentality of everybody who owns a car	We've got this shale gas which you know the technology has developed rather quickly, the US government has been in full support of it…it's creating a brand new gigantic vested interest around this non-renewable fuel As existing reserves are used up, the costs and risks of extraction will probably increase to a point where the becomes unsustainable
Congestion	Congestion of existing infrastructure and the economic burden that [it] poses	Congestion, especially in developing economies, will affect economic growth We can't meet existing demand, let alone what is coming out of China, which it's a joke when you see these projections of how many people are going to be driving cars there, that's just not going to be able to happen
Technology	Rapidly emerging vehicle-based technologies that fundamentally change how people consume transport as a product	Electric vehicles are a disruptive technology that is not being taken into account sufficiently in planning—and here I mean impacts on government revenue to finance maintenance of existing roading networks, not recharging infrastructure (which is not a big issue)
Demographics	Changes in the population demographics (include age profile), including changes in lifestyle preference and attitudes to transport	Impact of potentially 2 billion more cars on the road, by 2020, mainly in India and China Middle-classes in India, China etc. rapidly increasing transport demands for passengers and freight
Transport policy	Inefficient government systems	Tendency of governments to respond to rising fuel prices by reducing fuel taxes and subsidizing fuel production It's still basically supply-side orientation. In other words, improve the fuel economy and make sure we have an adequate supply of energy

The themes arising out of the Delphi study thus provided the scope of the model, and the individually stated propositions provided the basis for understanding the casual relationships. The method for achieving this is explained below.

The key themes identified in the Delphi study were of two types. The first set of themes were those seen to be shaping business-as-usual transport systems. These were:

- The availability and price of oil;
- Congestion;
- Technologies;
- Demographics; and
- Transport policy

The second set of themes were those that were seen to be drivers of change. These were:

- Changes in the availability and price of oil
- Investment in public and active transport;
- Increasing population density; and
- New technologies

These themes provided the key constructs within the model. The approach used in this paper to identify and use constructs was first articulated by Sastry (1997). The first task was to identify key constructs in the panel's responses that illustrated those key themes. The second task was to identify propositions stated by panel members that described how one construct interacted with and influenced another. The aim here was to build upon the understanding of the key themes obtained in the Delphi study to explore how they interacted and influenced each other. Table 1 shows examples of the thematic coding taken from the Delphi study, constructs that illustrate those themes, and propositions that capture panel members assertions about the casual relationships between these constructs.

The next step in building the model was to cluster the constructs and propositions to gain an understanding of the commonly expressed perspectives on causality across the many areas of expertise represented. We then depicted these as sets of interlinked drivers of the status quo (or of change) in relation to the dominant transport system. For example, the participants' combined narratives on the availability and price of oil described a number of causal relationships, some of which fed back to directly affect the availability and price, creating self-reinforcing loops of causality. The experts did not always agree, and where there was more than one view expressed about a given causal relationship, we included all, on the basis that this would assist in understanding the complexity of the system.

Across the panel's comments, we found that their propositions about business-as-usual tended to be more coherent than their propositions about change. Their statements about how observed trends might ultimately bring about transformational change were often implied rather than explicit. For example, a response to the question about threats to BAU was: "Increasing oil price (once fallout from global financial crisis passes) and peak car use will mean that assumptions about increasing private vehicle travel in line with historial trends may not eventuate". This statement implies a relationship between cost of fuel and use of private vehicles although the exact relationship is not spelt out. Other similar comments on threats to BAU included, 'increasing fuel prices', and 'rising private and public costs for use and maintenance [of private vehicles].' In situations such as this, where the mechanism of change was not made explicit, we made inferences about causal relationships informed by the literature. In the model, the causal chain that is developed from this and similar statements is that the 'price of fuel at the pump', affects the 'cost of running a private vehicle', which in turn affects the 'relative attractiveness of private vehicles'.

In order to understand the causal maps (Figs. 1, 2, 3, 4) two mapping conventions need to be explained. First, the use of '+' and '−' signs denote the influence of one factor on the other. For example, in Fig. 1 there is a causal arrow between concern for energy security and efforts to increase supply. The arrow indicates the direction of causal influence, the '+' sign indicates that if concern for energy security increases so will efforts to increase supply. Conversely if concern drops, so will the efforts. In Fig. 2 there is a causal arrow between infrastructure for cars and congestion. In this case the arrow has a '−' associated with it. In this case improved infrastructure for cars decreases congestion, and conversely any decline in infrastructure would contribute to increased congestion. To highlight these differences on the figures, positive causal influences are depicted with solid blue lines and negative causal influences are depicted with red dashed lines.

When a chain of such casual influences loops back on itself, a feedback loop is created, which can either be a reinforcing (R) loop or a balancing (B) loop. The behaviour of the loop is a result of the particular mix of positive '+' and '-'negative causal influences. Figure 1 depicts a positive feedback loop (R1) whereby each of the variables in the loop will incrementally grow the next variable, unless an external influence acts to slow or prevent this. In Fig. 2 there is a balancing feedback loop (B1) which has a mix of positive and negative causal influences, resulting in a feedback loop that tends towards an equilibrium.

The interactions between causal influences and their resulting feedback loops is what gives complex systems their dynamic behaviour. The technique of causal mapping aims to reflect this dynamism. Using the panel members' propositions we built up an SD model to represent the core concepts of the causal theory as collectively articulated by the panel. This theory is built up in stages in the following section, beginning with a core feedback loop and then building up to include additional causal processes.

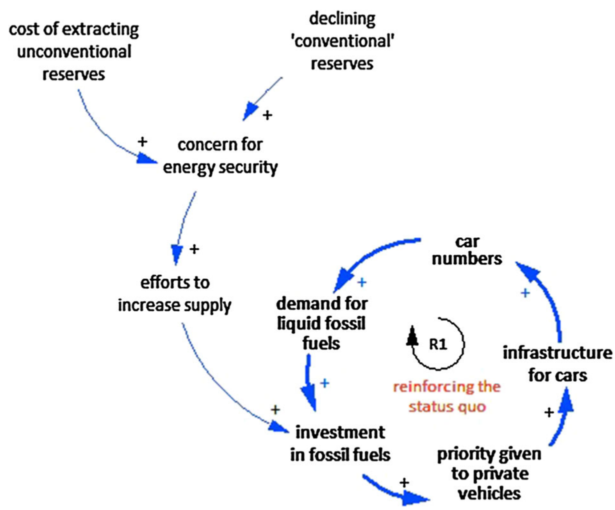

Fig. 1 Reinforcing the status quo

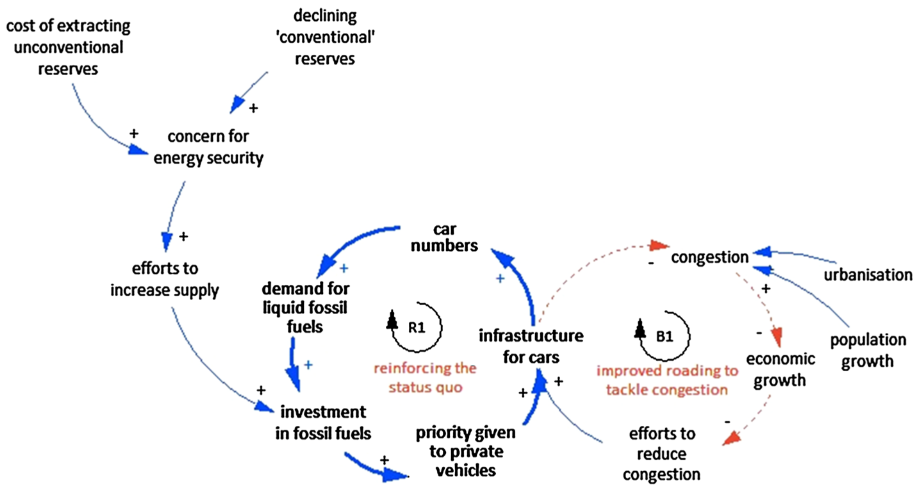

Fig. 2 Improved roading to tackle congestion

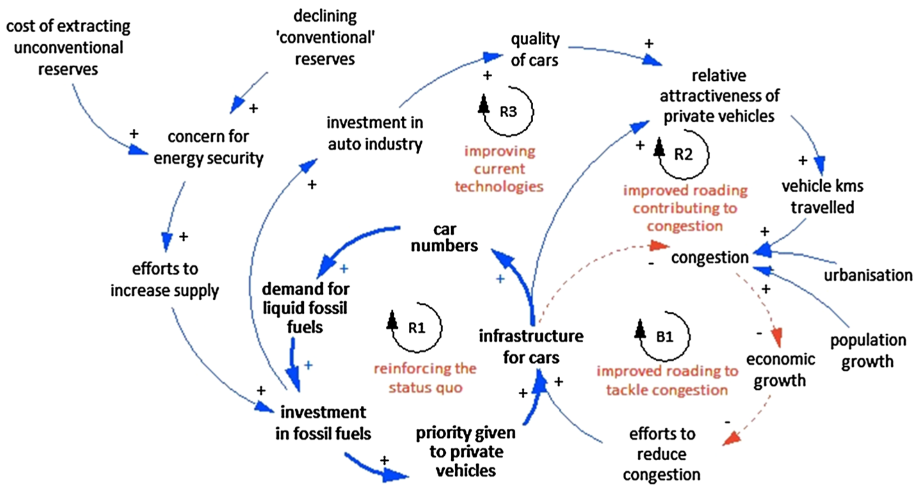

Fig. 3 Technology and roading

Results

Shaping business as ususal

The first stage of the causal model reflects the panel's statements about the main constructs that are reinforcing BAU in the transport system, namely the availability and price of oil; congestion; technologies; demographics; and transport policy. The core dynamic, underpinning the themes of 'availability and price of oil' and 'transport policy' is represented in Fig. 1 by the reinforcing loop R1 (*Reinforcing the Status Quo*), whereby prioritisation of the private car drives the development of car infrastructure, which stimulates growth in car

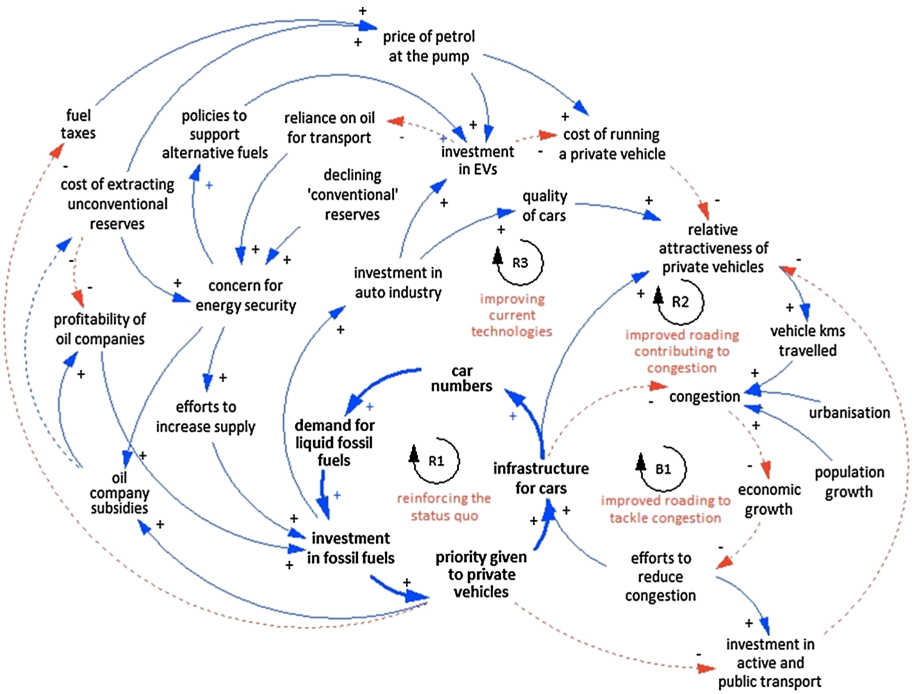

Fig. 4 Rising fuel prices and counterintuitive impact of electric vehicles

numbers, driving growth in demand for liquid fossil fuels, driving further investment in fossil fuel extraction. The causal chain to the side relates to the supply of fossil fuels, and shows that as conventional reserves decline, and the cost of extracting unconventional reserves increases, this drives concern for energy security and ramps up efforts to increase supply, the investment for which can only be supported if vehicle numbers continue to increase, thus the continued prioritisation of private cars.

This dynamic sits at the centre of many of the experts' discussions around stasis versus change, highlighting the difficulties in changing an established transport system based on the relationship between fossil fuels and private cars. This system of interrelated causal connections helps to maintain the status quo, despite the changing circumstances in fossil fuel supply.

In Fig. 2, a second causal loop is added: the balancing loop *Improved Roading to Tackle Congestion* (B1), which integrates the propositions relating to the key themes of congestion, demographics and transport policy. Here the external drivers of population growth and urbanisation are creating increasing congestion in cites, often severe enough to impact upon economic growth. For example, one expert referred to "congestion, saturation of existing infrastructure and the economic burden this poses, partly caused by population growth." To reduce the impact on growth, there are efforts to reduce congestion, which, along with the priority given to private vehicles, contributes to improved infrastructure for cars. This then reduces congestion and increases economic growth, but due to the ongoing pressures of population growth and urbanisation, as well as the transport-enhancing impact of economic growth, this is only partially successful, so congestion re-emerges and the cycle continues. This is a balancing loop because increased congestion leads to less economic growth, which drives efforts to reduce congestion by improving the infrastructure for cars, which briefly decreases the congestion until this itself stimulates more road use. This is the dynamic that is created when, as one participant described it there is a, “lack of integration in planning and policy/project evaluation, resulting in solutions to one problem that exacerbate other problems.”

Two additional reinforcing loops are shown in Fig. 3: *Improved Roading Contributing to Congestion* (R2) and *Improving Current Technologies* (R3), both of which help further embed automobility. Feedback loop R2 highlights how improving roading infrastructure as a solution to congestion is a double-edged sword. While improved roading can reduce congestion at least in the short-term, it further contributes to the relative attractiveness of private vehicles, increasing the vehicle kilometres travelled which, over time, contributes to further congestion, thus offsetting any gain short-term gain that may have been obtained. A similar story is evident in feedback loop R3, which incorporates the ‘technology’ theme, and which is driven by the ongoing investment in auto industry leading to increased quality of cars to maintain their appeal and competitiveness against alternative modes of transport.

This initial model synthesises the causal propositions made by panel members in relation to the key themes identified in the Delphi study as being ‘shapers of business-as-usual’. In doing so the model provides an initial theory of ‘policy resistance’ (Sterman 2006), highlighting how feedback effects can worsen the problem that is being addressed. In the above example the response to congestion only serves to make congestion worse over time. This occurs, Sterman argues, because in complex systems learning is often weak and slow, so that our ability to see how our interventions play out over space and time is limited, resulting in the interventions generating unintended consequences. To the extent that these unintended consequences undermine the solution, they become examples of ‘policy resistance’. This feature of dynamic systems is even more evident when we explore the drivers of change articulated by panel members.

Drivers of change

The key drivers of change identified by the panel were changes in the availability and price of oil; investment in public and active transport; increasing population density; and new technologies such as batteries, internet and 3D printing. If drivers of change are considered in the absence of an understanding of the dynamics that shape the status quo, inaccurate assumptions may be drawn. Mapping these drivers in the context of other causally related factors helps to reveal how they will drive change and whether they will in fact do so. The following sections describe each of these drivers, which become core constructs in the model, and the causal propositions that enabled the development of a causal theory comprising both the drivers of stasis and change. As previously, the process involved finding constructs that illustrated the key drivers of change identified in the Delphi study and causal propositions that described how one construct interacted with and influenced another.

Availability and price of oil

The strong influence of the availability and price of oil is captured in the model in Fig. 1 with the variables declining conventional reserves and cost of extracting unconventional reserves. Figure 4 shows a set of new factors that also make this situation a potentially volatile driver of change. In the absence of confounding factors such as subsidies, increasing extraction costs will ultimately impact the profitability of oil companies, which, over time, may decrease investment in them, and thereby slow down the reinforcing cycle (R1). These increasing extraction costs will also impact the price of petrol at the pump, increasing the cost of running a private vehicle and thereby reducing the relative attractiveness of motor vehicles. This is shown on the left hand side of Fig. 4.

This increasing price of fuel, along with government policies to support alternative fuels, are reported to be driving the development of new technologies, one of which is investment in electric vehicles (EVs), which has the potential to reduce the reliance on oil for transportation and thereby reduce concern for energy security and the consequential need for efforts to increase supply.

Investment in public and active transport

The panel also considered that policies and/or the dynamics around the price and availability of oil could deliver a further driver of change, namely investment in public and active transport (see lower RH corner of Fig. 4). If the availability and price of oil starts to increase the price of petrol at the pump, thereby increasing the cost of running a private vehicle, then the feedback signals could lead to a different response to urban congestion, i.e. investment in public and active transport. This would not only help to directly decrease congestion but also decrease the relative attractiveness of private vehicles, which would also help to reduce congestion by reducing the vehicle kms travelled by private cars.

Increasing population

Population growth, combined with urbanisation (RH side of Fig. 4) is currently increasing congestion in most larger cities. Increased population growth therefore increases the symptoms—in this case congestion—and this may create more demand for change. Whether this drives a change in the transport system or simply reinforces it, is subject to the dynamics noted in Sect. Investment in public and active transport. The choice here that determines the direction of the change is the response to congestion. Both increasing the infrastructure for cars and investment in public and active transport will help decrease congestion and thereby make urban living more attractive. Each option, however leads to much different cities.

New technologies

Similarly, new vehicle technologies associated with investment in the auto industry generally and investment in EVs more specifically have the potential to contribute to both change and to reinforcing BAU. Panel members identified improvements in battery technologies, for example, as potentially both increasing the range of EVs and decreasing their cost, thus contributing to maintaining and potentially increasing the relative attractiveness of private vehicles. While this may reduce the reliance on oil for transport, it would also serve to maintain the focus on private vehicles, and thereby potentially undermine investment in public and active transport. This is a complex feedback loop (R3), in which the increasing relative attractiveness of private vehicles, increases congestion, and driving the '*improved roading to tackle congestion*' feedback loop (B1). This in turn contributes to reinforcing the status quo (R1), completing the loop and driving further investment in the auto industry

Response to change drivers

Despite this range of potential destabilising influences identified by the panel the model also highlights feedback loops that could potentially undermine change influences (Fig. 4). The central feedback loop, 'reinforcing the staus quo' drives actions that offset these change forces, limiting the impact they may have. For example, the concern for energy security is so strong that governments do what they can to support oil companies to continue extracting new reserves, usually through a range of oil company subsidies, thus maintaining the investment in fossil fuels.

A second feedback loop, not specifically identified by the Delphi panel but inferred from the emerging causal model is that EVs having lower operating costs than cars with internal combustion engines, maintain, and possibly further increase, the relative attractiveness of private vehicles, and thereby ongoing investment in the transport system as currently configured, albeit fuelled by a different source.

A third loop is driven by the priority given to private vehicles ensuring that the effects of increased oil extraction costs is minimised. As a Delphi panel member argued, there is a "…tendency of governments to respond to rising fuel prices by reducing fuel taxes and subsidizing fuel production". This is captured in the model by the links from 'priority given to private vehicles', oil company subsidies, and 'government policies', which can work together to ensure that price rises at the pump, or their impacts, are minimized.

A fourth loop works against change is where the bulk of investments targeting congestion are spent on improved infrastructure for cars, thus minimizing investment in public and active transport.

Discussion

The analysis of the Delphi findings as reported in this paper has built a relatively simple causal model which reflects the key themes expressed by the Delphi participants. Based on the findings, it would be possible to continue the process of model-building and construct a model that was more detailed, with more linkages and feedback loops. For the purposes of this paper, however, our interest was in exploring the use of SD modelling to analyse Delphi data. The causal model produced from the analysis was a secondary aim. Here, we wished to avoid a model that was so nuanced and all-encompassing so as to reduce its value. Rather we purposely developed a model that consisted of a relatively small number of constructs and relationships, and which had a clear and coherent logic built from the expert panel's propositions.

As pointed out by Stepp et al. (2009) qualitative casual models can be useful in identifying the unintended consequences of policies so that it is only through a set of related policies that the end goal could be met. Furthermore, these can be used to identify the complementarity between policies that together could lead to improved outcomes, what Stepp et al. refer to as 'policy synergies'.

The findings show promise for the combination of Delphi and SD modelling in helping to identify such unintended consequences and policy synergies. In thinking about complex situations such as transport, it is too easy to consider only that part of the system that one is familiar with, and to become entrenched into linear thought processes. The combination of the Delphi and SD modelling can address both of these issues, offering enhanced insights by bringing together many expert views on the topic, and enabling non-linear processes such as feedback loops to be revealed.

The full model (Fig. 4) makes it clear that the BAU transport system is strongly contingent upon the continuation of the feedback loops R1-R3 and the balancing loop B1. If any of the factors that form these loops change markedly, then there is the potential for the system as a whole to change. Two themes stand out as potential game-changers. One is the relative investment in infrastructure to support private vehicles compared to infrastructure to support public and active transport. Even a relatively small change in relative expenditure, whereby congestion was not addressed by the provision of better roading, but by the provision of better public transport and active transport could have a marked impact, as congestion then decreases the attractiveness of private vehicles and becomes a driver to shift people out of private vehicles and into other transport forms (i.e. the reinforcing loop starts to work in the opposite direction).

The other highly complex area of interacting and competing forces is that represented by the left hand side of Fig. 4—the demand for and production of liquid fossil fuels. Panel members recognised that with the rapid emergence of unconventional sources of oil such as tar sands, fracking and deep sea oil, the cost of production would inevitably increase, but had mixed views on whether this would result in a continuation of BAU or drive a transport transition. If the price of fuel at the pump remained high it could continue to drive investment in EVs and battery technologies to a point where these became highly competitive and started to replace ICEs in significant numbers. If this then led to lower demand for liquid fossil fuels, there would be knock-on effects back through various linkages of the model which could be the start of a downward spiral for BAU. On the other hand, if government policies continue to support the linked systems of fossil fuels and private ICE cars, possibly driven by concerns about energy security and vested interests, then the current system is likely to continue for some time. The current drop in oil prices only serves to continue the focus on private vehicles, making change all that more difficult.

The model also reveals that EVs, often discussed as the solution to high levels of transport greenhouse gas emissions, are in many ways simply another replication of automobility. If the price and attractiveness of EVs are sufficiently compelling, they are likely to simply replace ICEs over time, so that the feedback loops relating to congestion (B1 and R1) will continue unabated. To stop the endless growth of congestion response loop R1, investment is required in active and public transport rather than responding to congestion, regardless of whether it is caused by EVs or ICEs.

Conclusion

We conclude that using the outcomes of a Delphi study with transport experts provides a rich source of qualitative material which is highly suitable for the basis of developing a system dynamics model. The informed perspectives expressed by the Delphi panel provided a rich source of material, and provided a range of causal arguments that were able to be built into a plausible and coherent theory of stasis and change in the dominant transport system.

The resulting model shows the complex, interdependent dynamics involved in supporting the status quo, which must change to achieve a transition to a more sustainable future. Even at the relatively high level of analysis reported here, the model is useful in revealing interdependencies between parts of the system, where change in one part may well have knock-on effects elsewhere in the system. In particular the model reveals the strong reinforcing loops that act to minimise the impact of change drivers and thus retain the dominance of automobility. The result is a system that is highly dependent on the continued existence of key reinforcements such as policies that subsidise fossil fuels. As noted in the discussion, the resulting SD model indicates opportunities for transition either by redirecting the existing reinforcing loops, or by the introduction of new pertubations into the system through policy or other means.

It should also be noted that this is the first stage of developing the model, and we have not attempted at this point to include all the drivers mentioned by the transport experts, nor some of the more intricate interactions mentioned. Health concerns and concerns about climate change were also frequently mentioned as potential change drivers, and these have not been included in this version of the model. The model thus represents a relatively simplified version of participants' perspectives and does not reflect the full heterogeneity of views expressed. This was intentional, as for the purposes of this paper we wished to focus on proof of concept rather than an exhaustive analysis. Future versions of the model will be broadened by incorporating other factors arising out of the Delphi study not currently included. Moreover, future research will develop the model by seeking to quantify some of the key causal links to assess the likely magnitude and potential direction of change, something that a purely qualitative model, such as that presented in this paper, is not able to do.

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